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Dictionary

Ⓓ **intrinsic pressure** [PHYSICS] Pressure in a fluid resulting from inward forces on molecules near the fluid surface, caused by attraction between molecules.Also known as internal pressure.
{ in'trin•sik 'presh•ər }

Score: 0.69

Ⓓ **intrinsic procedure** See built-in
{ in'trin•sik prə'sē•jər }

Score: 0.69

Ⓓ **intrinsic properties of a surface** [MATHEMATICS] A property of a surface which can be described without reference to the surrounding space.
{ in'trin•sik ¦präp•ərd•ēz əv ə 'sər•fəs }

Score: 0.69

Ⓓ **intrinsic property** [SOLID-STATE PHYSICS] A property of a substance that is not affected by impurities or imperfections in the crystal structure.
{ in'trin•sik 'präp•ərd•ē }

Score: 0.69

Ⓓ

intrinsic semiconductor [SOLID-STATE PHYSICS] A semiconductor in which the concentration of charge carriers is characteristic of the material itself rather than of the content of impurities and structural defects of the crystal.Also known as i-type semiconductor.
{ in'trin•sik ¦sem•i•kən¦dək•tər }

Score: 0.69

- **intrinsic temperature range** [SOLID-STATE PHYSICS] In a semiconductor, the temperature range in which its electrical properties are essentially not modified by impurities or imperfections within the crystal.
{ in'trin•sik 'tem•prə•chər ˌrānj }

Score: 0.69

- **intrinsic tracer** [NUCLEAR PHYSICS] An isotope that is present naturally in a form for tracing a given element through chemical and physical processes.
{ in'trin•sik 'trā•sər }

Score: 0.69

- **intrinsic variable star** [ASTRONOMY] A star that is variable not because of an
{ in'trin•sik ¦ver•ē•ə•bəl 'stär }

Score: 0.69

- **intrinsic viscosity** [PHYSICAL CHEMISTRY] The ratio of a solution's specific viscosity to the concentration of the solute, extrapolated to zero concentration.Also known as limiting viscosity number.
{ in'trin•sik vi'skäs•əd•ē }

Score: 0.69

- **semiconductor intrinsic properties** [SOLID-STATE PHYSICS] Properties of a semiconductor that are characteristic of the ideal crystal.
{ ¦sem•i•kən¦dək•tər in'trin•sik 'präp•ərd•ēz }

Score: 0.69

- **pnip transistor** [ELECTRONICS] An intrinsic junction transistor in which the intrinsic region is sandwiched between the n-type base and the p-type collector.
{ ¦pēˌenˌī¦pē tranˌzis•tər }

Score: 0.68

- **B-H meter** [ENGINEERING] A device used to measure the intrinsic hysteresis loop of a sample of magnetic material.
{ ¦bē¦āch ˌmēd•ər }

Score: 0.66

- **bismuth germinate detector** [NUCLEONICS] A high-efficiency, low-resolution detector of gamma rays that uses bismuth germinate (Bi4Ge3O12), an intrinsic scintillator, whose large gamma-ray absorption coefficient makes possible a reduction in detector size.
{ 'biz•məth ¦jer•məˌnāt diˌtek•tər }

Score: 0.66

- **blocked impurity band detector** [ELECTRONICS] A detector of long-wavelength infrared radiation consisting of a heavily doped extrinsic photoconductor on which an undoped intrinsic layer is grown epitaxially to prevent dark current from flowing in the impurity band.

{ 'bläkt im'pyůr•əd•ē ¦band di,tek•tər }

Score: 0.66

built-in function [COMPUTER SCIENCE] A function that is available through a simple reference and specification of arguments in a given higher-level programming language.Also known as built-in procedure; intrinsic procedure; standard function.
{ 'bilt,in 'fəŋk•shən }

Score: 0.66

Cepheid [ASTRONOMY] One of a subgroup of periodic variable stars whose brightness does not remain constant with time and whose period of variation is a function of intrinsic mean brightness.
{ 'sē•fē•əd }

Score: 0.66

characteristic acoustic impedance [ACOUSTICS] The product of the density and the speed of sound in a medium; it is analogous to the characteristic impedance of an infinitely long transmission line.Also known as intrinsic impedance.
{ ,kar•ik•tə'ris•tik ə'kü•stik im'pēd•əns }

Score: 0.66

Cnidaria [INVERTEBRATE ZOOLOGY] A phylum of the Radiata whose members typically bear tentacles and possess intrinsic nematocysts.Also known as Coelenterata.
{ nī'dar•ē•ə }

Score: 0.66

convection modulus [FLUID MECHANICS] An intrinsic property of a fluid which is important in determining the Nusselt number, equal to the acceleration of gravity times the volume coefficient of thermal expansion divided by the product of the kinematic viscosity and the thermal diffusivity.
{ kən'vek•shən ,mäj•ə•ləs }

Score: 0.66

diffused-alloy transistor [ELECTRONICS] A transistor in which the semiconductor wafer is subjected to gaseous diffusion to produce a nonuniform base region, after which alloy junctions are formed in the same manner as for an alloy-junction transistor; it may also have an intrinsic region, to give a pnip unit.Also known as drift transistor.
{ də¦fyüzd 'al,ȯi tran'zis•tər }

Score: 0.66

|◀◀ PREVIOUS 1 2 3 4 NEXT ▶▶|

Last modified: April 10, 2000

EXHIBIT D

Engineering & Materials: Electrical & Electronics
Engineering:Physical electronics
Physics: Solid state physics

Semiconductor

A solid crystalline material whose electrical conductivity is intermediate between that of a metal and an insulator. Semiconductors exhibit conduction properties that may be temperature-dependent, permitting their use as thermistors (temperature-dependent resistors), or voltage-dependent, as in varistors. By making suitable contacts to a semiconductor or by making the material suitably inhomogeneous, electrical rectification and amplification can be obtained. Semiconductor devices, rectifiers, and transistors have replaced vacuum tubes almost completely in low-power electronics, making it possible to save volume and power consumption by orders of magnitude. In the form of integrated circuits, they are vital for complicated systems. The optical properties of a semiconductor are important for the understanding and the application of the material. Photodiodes, photoconductive detectors of radiation, injection lasers, light-emitting diodes, solar-energy conversion cells, and so forth are examples of the wide variety of optoelectronic devices. See also: Integrated circuits; Laser; Light-emitting diode; Photodiode; Photoelectric devices; Semiconductor diode; Semiconductor rectifier ; Thermistor; Transistor; Varistor

Conduction in Semiconductors

The electrical conductivity of semiconductors ranges from about 10^3 to 10^{-9} ohm^{-1} cm^{-1}, as compared with a maximum conductivity of 10^7 for good conductors and a minimum conductivity of 10^{-17} ohm^{-1} cm^{-1} for good insulators. See also: Electric insulator; Electrical conductivity of metals

The electric current is usually due only to the motion of electrons, although under some conditions, such as very high temperatures, the motion of ions may be important. The basic distinction between conduction in metals and in semiconductors is made by considering the energy bands occupied by the conduction electrons. See also: Ionic crystals

A crystalline solid consists of a large number of atoms brought together into a regular array called a crystal lattice. The electrons of an atom can each have certain energies, so-called energy levels, as predicted by quantum theory. Because the atoms of the crystal are in close proximity, the electron orbits around different atoms overlap to some extent, and the electrons interact with each other; consequently the sharp, well-separated energy levels of the individual electrons actually spread out into energy bands. Each energy band is a quasicontinuous group of closely spaced energy levels. See also: Band theory of solids

At absolute zero temperature, the electrons occupy the lowest possible energy levels, with the restriction that at most two electrons with opposite spin may be in the same energy level. In semiconductors and insulators, there are just enough electrons to fill completely a number of energy bands, leaving the rest of the energy bands empty. The highest filled energy band is called the valence band. The next higher band, which is empty at absolute zero temperature, is

called the conduction band. The conduction band is separated from the valence band by an energy gap which is an important characteristic of the semiconductor. In metals, the highest energy band that is occupied by the electrons is only partially filled. This condition exists either because the number of electrons is not just right to fill an integral number of energy bands or because the highest occupied energy band overlaps the next higher band without an intervening energy gap. The electrons in a partially filled band may acquire a small amount of energy from an applied electric field by going to the higher levels in the same band. The electrons are accelerated in a direction opposite to the field and thereby constitute an electric current. In semiconductors and insulators, the electrons are found only in completely filled bands, at low temperatures. In order to increase the energy of the electrons, it is necessary to raise electrons from the valence band to the conduction band across the energy gap. The electric fields encountered are not large enough to accomplish this with appreciable probability. At sufficiently high temperatures, depending on the magnitude of the energy gap, a significant number of valence electrons gain enough energy thermally to be raised to the conduction band. These electrons in an unfilled band can easily participate in conduction. Furthermore, there is now a corresponding number of vacancies in the electron population of the valence band. These vacancies, or holes as they are called, have the effect of carriers of positive charge, by means of which the valence band makes a contribution to the conduction of the crystal. See also: Hole states in solids

The type of charge carrier, electron or hole, that is in largest concentration in a material is sometimes called the majority carrier and the type in smallest concentration the minority carrier. The majority carriers are primarily responsible for the conduction properties of the material. Although the minority carriers play a minor role in electrical conductivity, they can be important in rectification and transistor actions in a semiconductor.

Electron distribution

The probability *f* for an energy level *E* to be occupied by an electron is given by the Fermi-Dirac distribution function (1) , where *k*

$$f = \left[1 + \exp\left(\frac{E - W}{kT}\right)\right]^{-1} \tag{1}$$

is the Boltzmann constant and *T* the absolute temperature. The parameter *W* is the Fermi energy level; an energy level at *W* has a probability of 1/2 to be occupied by an electron. The Fermi level is determined by the distribution of energy levels and the total number of electrons. See also: Fermi-Dirac statistics

In a semiconductor, the number of conduction electrons is normally small compared with the number of energy levels in the conduction band, and the probability for any energy level to be occupied is small. Under such a condition, the concentration of conduction electrons is given by Eq. (2) , where *h* is Planck's

$$N_n = \frac{2}{h^3}(2\pi m_n kT)^{3/2} \exp\left(\frac{W - E_c}{kT}\right) \tag{2}$$

constant, E_c is the lowest energy of the conduction band, and m_n is called the effective mass of conduction electrons. The effective mass is used in place of the actual mass to correct the coefficient in the equation and to bring the results in line with experimental observations. This correction is necessary because the theory leading to these equations is based upon electrons moving in a field free space, which is not the exact picture. The electrostatic Coulomb potential throughout the crystal is varying in a periodic manner, the variation being due to the electric

fields around the atomic centers. The concentration of holes in the valence band is given by Eq. (3) ,

$$N_p = \frac{2}{h^3}(2\pi m_p kT)^{3/2} \exp\left(\frac{E_v - W}{kT}\right) \quad (3)$$

where m_p is the effective mass of a hole and E_v is the highest energy of the valence band.

Mobility of carriers

The velocity acquired by charge carriers per unit strength of applied electric field is called the mobility of the carriers. The velocity in question is the so-called drift velocity in the direction of the force exerted on the carriers by the applied field. It is added to the random thermal velocity. In semiconductors the carrier mobility normally ranges from 10^2 to 10^5 $cm^2/(s)(V)$. A material's conductivity is the product of the charge, the mobility, and the carrier concentration.

Electrons in a perfectly periodic potential field can be accelerated freely. Impurities, physical defects in the structure, and thermal vibrations of the atoms disturb the periodicity of the potential field in the crystal, thereby scattering the moving carriers. It is the resistance produced by this scattering that limits the carriers to only a drift velocity under the steady force of an applied field.

Intrinsic semiconductors

A semiconductor in which the concentration of charge carriers is characteristic of the material itself rather than of the content of impurities and structural defects of the crystal is called an intrinsic semiconductor. Electrons in the conduction band and holes in the valence band are created by thermal excitation of electrons from the valence to the conduction band. Thus an intrinsic semiconductor has equal concentrations of electrons and holes. The intrinsic carrier concentration N_i is determined by Eq. (4) ,

$$N_i = \frac{2}{h^3}(2\pi kT)^{3/2}(m_n m_p)^{3/4} \exp\left(-\frac{E_g}{2kT}\right) \quad (4)$$

where E_g is the energy gap. The carrier concentration, and hence the conductivity, is very sensitive to temperature and depends strongly on the energy gap. The energy gap ranges from a fraction of 1 eV to several electronvolts. A material must have a large energy gap to be an insulator.

Extrinsic semiconductors

Typical semiconductor crystals such as germanium and silicon are formed by an ordered bonding of the individual atoms to form the crystal structure. The bonding is attributed to the valence electrons which pair up with valence electrons of adjacent atoms to form so-called shared pair or covalent bonds. These materials are all of the quadrivalent type; that is, each atom contains four valence electrons, all of which are used in forming the crystal bonds. See also: Crystal structure

Atoms having a valence of +3 or +5 can be added to a pure or intrinsic semiconductor material with the result that the +3 atoms will give rise to an unsatisfied bond with one of the valence electrons of the semiconductor atoms, and +5 atoms will result in an extra or free electron that

is not required in the bond structure. Electrically, the +3 impurities add holes and the +5 impurities add electrons. They are called acceptor and donor impurities, respectively. Typical valence +3 impurities used are boron, aluminum, indium, and gallium. Valence +5 impurities used are arsenic, antimony, and phosphorus.

Semiconductor material "doped" or "poisoned" by valence +3 acceptor impurities is termed *p*-type, whereas material doped by valence +5 donor material is termed *n*-type. The names are derived from the fact that the holes introduced are considered to carry positive charges and the electrons negative charges. The number of electrons in the energy bands of the crystal is increased by the presence of donor impurities and decreased by the presence of acceptor impurities. Let N be the concentration of electrons in the conduction band and let P be the hole concentration in the valence band. For a given semiconductor, the relation $NP = N_i^2$ holds, independent of the presence of impurities. The effect of donor impurities tends to make N larger than P, since the extra electrons given by the donors will be found in the conduction band even in the absence of any holes in the valence band. Acceptor impurities have the opposite effect, making P larger than N. See also: Acceptor atom; Donor atom

At sufficiently high temperatures, the intrinsic carrier concentration becomes so large that the effect of a fixed amount of impurity atoms in the crystal is comparatively small and the semiconductor becomes intrinsic. When the carrier concentration is predominantly determined by the impurity content, the conduction of the material is said to be extrinsic. There may be a range of temperature within which the impurity atoms in the material are practically all ionized; that is, they supply a maximum number of carriers. Within this temperature range, the so-called exhaustion range, the carrier concentration remains nearly constant. At sufficiently low temperatures, the electrons or holes that are supplied by the impurities become bound to the impurity atoms. The concentration of conduction carriers will then decrease rapidly with decreasing temperature, according to either exp $(-E_i/kT)$ or exp $(-E_i/2kT)$, where E_i is the ionization energy of the dominant impurity.

Physical defects in the crystal structure may have similar effects as donor or acceptor impurities. They can also give rise to extrinsic conductivity.

An isoelectronic impurity, that is, an atom which has the same number of valence electrons as the host atom, does not bind individual carriers as strongly as a donor or an acceptor impurity. However, it may show an appreciable binding for electron hole pairs, excitons, and thereby have important effects on the properties. An example is nitrogen substituting for phosphorus in gallium phosphide; the impurity affects the luminescence of the material.

Hall effect

Whether a given sample of semiconductor material is *n*- or *p*-type can be determined by observing the Hall effect. If an electric current is caused to flow through a sample of semiconductor material and a magnetic field is applied in a direction perpendicular to the current, the charge carriers are crowded to one side of the sample, giving rise to an electric field perpendicular to both the current and the magnetic field. This development of a transverse electric field is known as the Hall effect. The field is directed in one or the opposite direction depending on the sign of the charge of the carrier. See also: Hall effect

The magnitude of the Hall effect gives an estimate of the carrier concentration. The ratio of the transverse electric field strength to the product of the current and the magnetic field strength is called the Hall coefficient, and its magnitude is inversely proportional to the carrier concentration. The coefficient of proportionality involves a factor which depends on the energy distribution of the carriers and the way in which the carriers are scattered in their motion. However, the value of this factor normally does not differ from unity by more than a factor of 2.

The situation is more complicated when more than one type of carrier is important for the conduction. The Hall coefficient then depends on the concentrations of the various types of carriers and their relative mobilities.

The product of the Hall coefficient and the conductivity is proportional to the mobility of the carriers when one type of carrier is dominant. The proportionality involves the same factor which is contained in the relationship between the Hall coefficient and the carrier concentration. The value obtained by taking this factor to be unity is referred to as the Hall mobility.

Materials and Their Preparation

The group of chemical elements which are semiconductors includes germanium, silicon, gray (crystalline) tin, selenium, tellurium, and boron.

Elemental semiconductors

Germanium, silicon, and gray tin belong to group IV of the periodic table and have crystal structures similar to that of diamond. Germanium and silicon are two of the best-known semiconductors. They are used extensively in devices such as rectifiers and transistors. Gray tin is a form of tin which is stable below 13°C (55°F). White tin, which is stable at higher temperatures, is metallic. Gray tin has a small energy gap and a rather large intrinsic conductivity, about 5×10^3 ohm^{-1} cm^{-1} at room temperature. The *n*-type and *p*-type gray tins can be obtained by adding aluminum and antimony, respectively.

Selenium and tellurium both have a similar structure, consisting of spiral chains located at the corners and centers of hexagons. The structure gives rise to anisotropy of the properties of single crystals; for example, the electrical resistivity of tellurium along the direction of the chains is about one-half the resistivity perpendicular to this direction. Selenium has been widely used in the manufacture of rectifiers and photocells.

Semiconducting compounds

A large number of compounds are known to be semiconductors. Copper(I) oxide (Cu_2O) and mercury(II) indium telluride ($HgIn_2Te_4$) are examples of binary and ternary compounds. The series zinc sulfide (ZnS), zinc selenide (ZnSe), and zinc telluride (ZnTe), and the series zinc selenide (ZnSe), cadmium selenide (CdSe), and mercury(II) selenide (HgSe) are examples of binary compounds consisting of a given element in combinations with various elements of another column in the periodic table. The series magnesium antimonide (Mg_2Sb_2), magnesium telluride (MgTe), and magnesium iodide (MgI_2) is an example of compounds formed by a given element with elements of various other columns in the periodic table. See also: Periodic table

A group of semiconducting compounds of the simple type AB consists of elements from columns symmetrically placed with respect to column IV of the periodic table. Indium antimonide (InSb), cadmium telluride (CdTe), and silver iodide (AgI) are examples of III-V, II-IV, and I-VI compounds, respectively. The various III-V compounds are being studied extensively, and many practical applications have been found for these materials. Some of these compounds have the highest carrier mobilities known for semiconductors. The compounds have zincblende crystal structure which is geometrically similar to the diamond structure possessed by the elemental semiconductors, germanium and silicon, of column IV, except that the four nearest neighbors of each atom are atoms of the other kind. The II-VI compounds, zinc sulfide (ZnS) and cadmium sulfide (CdS), are used in photoconductive devices. Zinc sulfide is also used as a luminescent material. See also: Luminescence; Photoconductivity

Binary compounds of the group lead sulfide (PbS), lead selenide (PbSe), and lead telluride (PbTe) are sensitive in photoconductivity and are used as detectors of infrared radiation. The compounds, bismuth telluride (Bi_2Te_3) and bismuth selenide (Bi_2Se_3), consisting of heavy atoms, are found to be good materials for thermocouples used for refrigeration or for conversion of heat to electrical energy. See also: Thermoelectricity

The metal oxides usually have large energy gaps. Thus pure oxides are usually insulators of high resistivity. However, it may be possible to introduce into some of the oxides impurities of low ionization energies and thus obtain relatively good extrinsic conduction. Copper(I) oxide (Cu_2O) was one of the first semiconductors used for rectifiers and photocells: extrinsic *p*-type conduction is obtained by producing an excess of oxygen over the stoichiometric composition, that is, the 2-to-1 ratio of copper atoms to oxygen atoms. A number of oxide semiconductors can be obtained by replacing some of the normal metal atoms with metal atoms of one more or less valency. The method is called controlled valence. An example of such a semiconductor is nickel oxide containing lithium.

Some compounds with rare-earth or transition-metal ions in their composition, such as EuTe and NiS_2, are semiconductors with magnetic properties. Another interesting type of semiconductor is characterized by layered structures. The interaction within a layer is significantly stronger than that between layers. A number of semiconductors of this type are known, such as PbI_2, GaSe, and various transition-metal dichalcogenides such as $SnSe_2$ and MoS_2.

Preparation of materials

The properties of semiconductors are extremely sensitive to the presence of impurities. It is therefore desirable to start with the purest available materials and to introduce a controlled amount of the desired impurity. The zone-refining method is often used for further purification of obtainable materials. The floating zone technique can be used, if feasible, to prevent any contamination of molten material by contact with crucible. See also: Zone refining

For basic studies as well as for many practical applications, it is desirable to use single crystals. Various methods are used for growing crystals of different materials. For many semiconductors, including germanium, silicon, and the III-V compounds, the Czochralski method is commonly used. The method of condensation from the vapor phase is used to grow crystals of a number of semiconductors, for instance, selenium and zinc sulfide. For materials of high melting points, such as various metal oxides, the flame fusion or Vernonil method may be used. See also: Crystal growth

The introduction of impurities, or doping, can be accomplished by simply adding the desired quantity to the melt from which the crystal is grown. Normally, the impurity has a small segregation coefficient, which is the ratio of equilibrium concentrations in the solid and the liquid phases of the material. In order to obtain a desired impurity content in the crystal, the amount added to the melt must give an appropriately larger concentration in the liquid. When the amount to be added is very small, a preliminary ingot is often made with a larger content of the doping agent; a small slice of the ingot is then used to dope the next melt accurately. Impurities which have large diffusion constants in the material can be introduced directly by holding the solid material at an elevated temperature while this material is in contact with the doping agent in the solid or the vapor phase.

A doping technique, ion implantation, has been developed and used extensively. The impurity is introduced into a layer of semiconductor by causing a controlled dose of highly accelerated impurity ions to impinge on the semiconductor. See also: Ion implantation

An important subject of scientific and technological interest is amorphous semiconductors. In an amorphous substance the atomic arrangement has some short-range but no long-range order. The representative amorphous semiconductors are selenium, germanium, and silicon in their amorphous states, and arsenic and germanium chalcogenides, including such ternary systems as Ge-As-Te. Some amorphous semiconductors can be prepared by a suitable quenching procedure from the melt. Amorphous films can be obtained by vapor deposition.

Rectification in Semiconductors

In semiconductors, narrow layers can be produced which have abnormally high resistances. The resistance of such a layer is nonohmic; it may depend on the direction of current, thus giving rise to rectification. Rectification can also be obtained by putting a thin layer of semiconductor or insulator material between two conductors of different material.

Barrier layer

A narrow region in a semiconductor which has an abnormally high resistance is called a barrier layer. A barrier may exist at the contact of the semiconductor with another material, at a crystal boundary in the semiconductor, or at a free surface of the semiconductor. In the bulk of a semiconductor, even in a single crystal, barriers may be found as the result of a nonuniform distribution of impurities. The thickness of a barrier layer is small, usually 10^{-3} to 10^{-5} cm.

A barrier is usually associated with the existence of a space charge. In an intrinsic semiconductor, a region is electrically neutral if the concentration n of conduction electrons is equal to the concentration p of holes. Any deviation in the balance gives a space charge equal to $e(p - n)$, where e is the charge on an electron. In an extrinsic semiconductor, ionized donor atoms give a positive space charge and ionized acceptor atoms give a negative space charge. Let N_d and N_a be the concentrations of ionized donors and acceptors, respectively. The space charge is equal to $e(p - n + N_d - N_a)$.

A space charge is associated with a variation of potential. A drop in potential $-\Delta V$ increases the potential energy of an electron by $e\Delta V$; consequently every electronic energy level in the semiconductor is shifted by this amount. With a variation of potential, the electron concentration varies proportionately to $\exp(eV/kT)$ and the hole concentration varies as $\exp(-eV/kT)$. A space charge is obtained if the carriers, mainly the majority carriers, fail to balance the charge of the ionized impurities.

A conduction electron in a region where the potential is higher by ΔV must have an excess energy of $e\Delta V$ in order for it to have the minimum energy on reaching the low potential region. Electrons with less energy cannot pass over to the low potential region. Thus a potential variation presents a barrier to the flow of electrons from high to low potential regions. It also presents a barrier to the flow of holes from low to high potential regions.

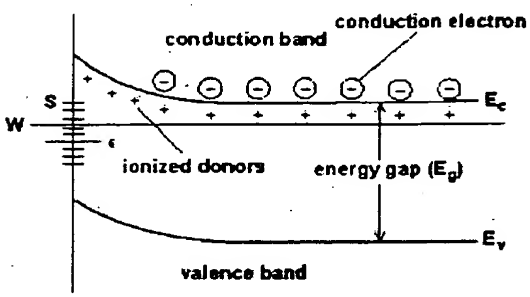
Surface barrier

A thin layer of space charge and a resulting variation of potential may be produced at the surface of a semiconductor by the presence of surface states. Electrons in the surface states are bound to the vicinity of the surface, and the energy levels of surface states may lie within the energy gap. Surface states may arise from the adsorption of foreign atoms. Even a clean surface may introduce states which do not exist in the bulk material, simply by virtue of being the boundary of the crystal.

The surface is electrically neutral when the surface states are filled with electrons up to a certain

energy level ϵ in the energy gap E_g, which is the energy difference between the bottom of the conduction band E_c and the top of the valence band E_v. If the Fermi level W in the bulk semiconductor lies higher in the energy gap, more surface states would be filled, giving the surface a negative charge. As a result the potential drops near the surface and the energy bands are raised for *n*-type material (Fig. 1). With the rise of the conduction band, the electron concentration is reduced and a positive space charge due to ionized donors is obtained. The amount of positive space charge is equal to the negative surface charge given by the electrons in the surface states between ϵ and the Fermi level.

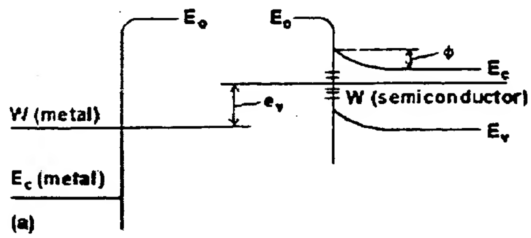
Fig. 1 Energy diagram of a surface barrier as employed in an *n*-type semiconductor.

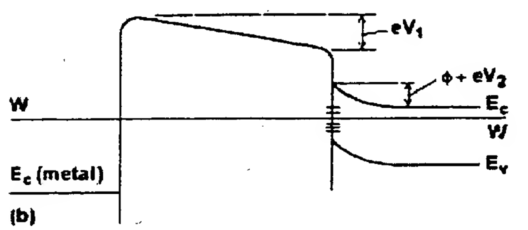


Contact barrier

The difference between the potential energy E_o of an electron outside a material and the Fermi level in the material is called the work function of the material. Figure 2 shows the energy diagram for a metal and a semiconductor, the work functions of which differ by eV. Upon connecting the two bodies electrically, charge is transferred between them so that the potential of the semiconductor is raised relative to that of the metal; that is, the electron energy levels in the semiconductor are lowered. Equilibrium is established when the Fermi level is the same in the two bodies. In this case, the metal is charged negatively and the semiconductor is charged positively. The negative charge on the metal is concentrated close to the surface, as is expected in good conductors. The positive charge on the semiconductor is divided between the increase of space charge in an extension of the barrier and the depopulation of some of the surface states. The charging of the semiconductor is brought about by a change of eV_2 in the barrier height ϕ. The sum of eV_2 and the potential energy variation eV_1 in the space between the two bodies is equal to the original difference eV between the work functions.

Fig. 2 Energy diagram for a metal (left) and an *n*-type semiconductor (right). E_0 is the potential energy of an electron outside the material, E_c is the energy at the bottom of the conduction band, and Ev is the energy at the top of the valence band. (*a*) Semiconductor and metal isolated. (*b*) Semiconductor and metal in electrical contact, $eV_1 + eV_2 = eV$.





With decreasing separation between the two bodies, the division of eV will be in favor of eV_2. However, if there is a very large density of states, a small eV_2 gives a large surface charge on the semiconductor due to the depopulation of surface states.

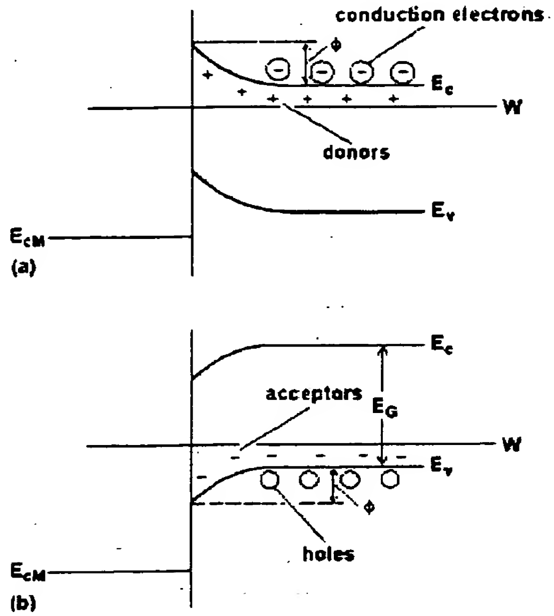
It is possible that eV_2 is limited to a small value even at the smallest separation, of the order of an interatomic distance in solids. In such cases, the barrier height remains nearly equal to the value ϕ of the free surface, irrespective of the body in contact. This situation has been found in germanium and silicon rectifiers. Before the explanation was given by J. Bardeen, who postulated the existence of surface states, it had been assumed that the height of a contact barrier was equal to the difference of the work functions.

The understanding and the application of metal-semiconductor contacts have been extended to various kinds of contacts, such as that between different semiconductors, heterojunctions, and metal oxide semiconductor (MOS) junctions.

Single-carrier theory

The phenomenon of rectification at a crystal barrier can be described according to the role played by the carriers. Where the conduction property of the rectifying barrier is determined primarily by the majority carriers, the single-carrier theory is employed. Such cases are likely to be found in semiconductors with large energy gaps, for instance, oxide semiconductors. Figure 3 shows the energy diagrams of metal-semiconductor contact rectifiers under conditions of equilibrium. The potential variation in the semiconductor is such as to reduce the majority carrier concentration near the contact. If the energy bands were to fall in the case of an *n*-type semiconductor or to rise in the case of a *p*-type semiconductor, the majority carrier concentration would be enhanced near the contact, and the contact would not present a large and rectifying resistance. It is clear that in the cases shown in Fig. 3 , the minority carrier concentration increases near the contact. However, if the energy gap is large, the minority carrier concentration is normally very small, and the role of minority carriers may be still negligible even if the concentration is increased.

Fig. 3 Energy diagrams of a rectifying contact between a metal and a semiconductor: (*a*) *n*-type semiconductor; (*b*) *p*-type semiconductor.

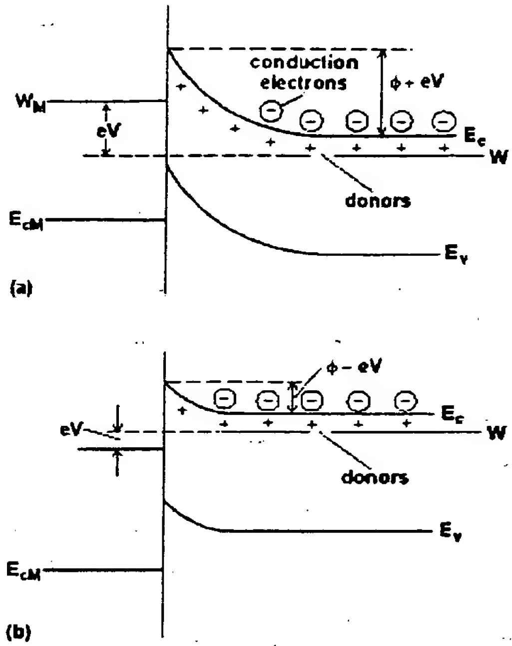


Under equilibrium conditions, the number of carriers passing from one body to the other is balanced by the number of carriers crossing the contact in the opposite direction, and there is no net current. The carriers crossing the contact in either direction must have sufficient energies to pass over the peak of the barrier. The situations under applied voltages are shown in Fig. 4 for the case of an *n*-type semiconductor. When the semiconductor is made positive, its energy bands are depressed and the height of the potential barrier is increased, as shown in Fig. 4*a* . Fewer electrons in the semiconductor will be able to cross over into the metal, whereas the flow of electrons across the contact from the metal side remains unchanged. Consequently, there is a net flow of electrons from the metal to the semiconductor. The flow of electrons from the metal side is the maximum net flow obtainable. With increasing voltage, the current saturates and the resistance becomes very high. Figure 4*b* shows the situation when the semiconductor is negative under the applied voltage. The energy bands in the semiconductor are raised. The flow of electrons from the semiconductor to the metal is increased, since electrons of lower energy are able to go over the peak of the barrier. The result is a net flow of electrons from the semiconductor to the metal. There is no limit to the flow in this case. In fact, the electron current increases faster than the applied voltage because there are increasingly more electrons at lower energies. The resistance decreases, therefore, with increasing voltage. The direction of current for which the resistance is low is called the forward direction, while the opposite is called the reverse or blocking direction. A general expression for the current can be written in the form of Eq. (5) , where *j* is

$$j = enC\left(\exp\frac{-\phi}{kT}\right)\left[\exp\left(\frac{eV}{kT}\right) - 1\right] \tag{5}$$

the current density, *n* is the carrier concentration in the bulk of the semiconductor, ϕ is the barrier height, and *V* is the applied voltage taken as positive in the forward direction. The factor *C* depends on the theory appropriate for the particular case.

Fig. 4 Energy diagrams of a rectifying contact between a metal and an *n*-type semiconductor under an applied voltage *V*. (*a*) Positive semiconductor. There is a net flow of electrons from metal to semiconductor. (*b*) Negative semiconductor. There is a net flow of electrons from semiconductor to metal.



Diffusion theory

When there is a variation of carrier concentration, a motion of the carriers is produced by diffusion in addition to the drift determined by the mobility and the electric field. The transport of carriers by diffusion is proportional to the carrier concentration gradient and the diffusion constant. The diffusion constant is related to the mobility, and both are determined by the scattering suffered by moving carriers. The average distance traveled by a carrier in its random thermal motion between collisions is called the mean free path. If barrier thickness is large compared to mean free path of carriers, motion of carriers in the barrier can be treated as drift and diffusion. This viewpoint is the basis of the diffusion theory of rectification. According to this theory, the factor C in Eq. (5) depends on the mobility and the electric field in the barrier.

Diode theory

When the barrier thickness is comparable to or smaller than the mean free path of the carriers, then the carriers cross the barrier without being scattered, much as in a vacuum tube diode.

According to this theory, the factor C in the rectifier equation is $v/4$, where v is the average thermal velocity of the carriers.

Tunneling theory

Instead of surmounting a potential barrier, carriers have a probability of penetrating through the barrier. The effect, called tunneling, becomes dominant if the barrier thickness is sufficiently small. This effect is important in many applications. See also: Tunneling in solids

Two-carrier theory

Often the conduction through a rectifying barrier depends on both electron and hole carriers. An important case is the *pn* junction between *p*- and *n*-sections of a semiconductor material. Also, in metal-semiconductor rectifiers, the barrier presents an obstacle for the flow of majority carriers but not for the flow of minority carriers, and the latter may become equally or more

important.

Rectification at pn junctions

A *pn* junction is the boundary between a *p*-type region and an *n*-type region of a semiconductor. When the impurity content varies, there is a variation of electron and hole concentrations. A variation of carrier concentrations is related to a shift of the energy bands relative to the constant Fermi level. This is brought about by a variation of the electrostatic potential which requires the existence of a space charge. If the impurity content changes greatly within a short distance, a large space charge is obtained within a narrow region. Such is the situation existing in a rectifying *pn* junction..

When a voltage is applied to make the *n*-region negative relative to the *p*-region, electrons flow from the *n*-region, where they are abundant, into the *p*-region. At the same time, holes flow from the *p*-region, where holes are abundant, into the *n*-region. The resistance is therefore relatively low. The direction of current in this case is forward. Clearly, the resistance will be high for current in the reverse direction.

With a current in the forward direction, electrons in the *n*-region and holes in the *p*-region flow toward the junction and there must be continuous hole-electron recombination in the neighborhood of the junction. The minority carrier concentration in each region is increased near the junction because of the influx of the carriers from the other region. This phenomenon is known as carrier injection. When there is a current in the reverse direction, there must be a continuous generation of holes and electrons in the neighborhood of the junction, from which electrons flow out into the *n*-region and holes flow out into the *p*-region. Thus current through a *pn* junction is controlled by the hole-electron recombination or generation in the vicinity of the junction.

The transistor consists of two closely spaced *pn* junctions in a semiconductor with an order *pnp* or *npn*.

Contact rectification

If the height of a rectifying contact barrier is high, only a very small fraction of majority carriers can pass over the barrier. The fraction may be so small as to be comparable with the concentration of the minority carriers, provided the energy gap is not too large. The current due to the minority carriers becomes appreciable if the barrier height above the Fermi level approaches the energy difference between the Fermi level and the top of the valence band (Fig. 3).

The concentration of minority carriers is higher at the contact than in the interior of the semiconductor. With a sufficiently high barrier, it is possible to obtain at the contact a minority carrier concentration higher than that of the majority carriers. The small region where this condition occurs is called the inversion layer.

As in the case of a *pn* junction, a forward current produces injection of minority carriers. With the presence of an inversion layer, the injection can be so strong as to increase appreciably the conductivity in the vicinity of the contact. Ordinarily, contact rectifiers consist of a semiconductor in contact with a metal whisker. For large forward currents, the barrier resistance is small, and the resistance of the rectifier is determined by the spreading resistance of the semiconductor for a contact of small area. By increasing the conductivity in the vicinity of the contact where the spreading resistance is concentrated, carrier-injection may reduce considerably the forward resistance of the rectifier.

Surface electronics

The surface of a semiconductor plays an important role technologically, for example, in field-effect transistors and charge-coupled devices. Also, it presents an interesting case of two-dimensional systems where the electric field in the surface layer is strong enough to produce a potential wall which is narrower than the wavelengths of charge carriers. In such a case, the electronic energy levels are grouped into subbands, each of which corresponds to a quantized motion normal to the surface, with a continuum for motion parallel to the surface. Consequently, various properties cannot be trivially deduced from those of the bulk semiconductor. See also: Charge-coupled devices; Surface physics

H. Y. Fan

BIBLIOGRAPHY

- M. L. Cohen and J. R. Chelikowsky, *Electronic Structure and Optical Properties of Semiconductors*, 2d ed., 1988
- K. Seeger, *Semiconductor Physics*, 7th ed., 1999
- M. Shur, *Physics of Semiconductor Devices*, 1996
- J. Singh, *Semiconductor Devices: An Introduction*, 1994
- S. Sze, *Physics of Semiconductor Devices*, 2d ed., 1981
- S. Wang, *Fundamentals of Semiconductor Theory and Device Physics*, 1989
- R. K. Willardson et al. (eds.), *Semiconductors and Semimetals*, vols. 1-42, 1966-1994
- M. Zambuto, *Semiconductor Devices*, 1989

DOI 10.1036/1097-8542.614010

EXHIBIT E

Search Results

AccessScience Wizard

You searched for:

words: channel
in: definition

Your search found **150** entries:
Refine your search ? Note: using AND, OR, and NOT will help.

Dictionary

- **channel** [CHEMICAL ENGINEERING] In percolation filtration, a portion of the clay bed where there is a preponderance of flow. [CIVIL ENGINEERING] A natural or artificial waterway connecting two bodies of water or containing moving water. [COMMUNICATIONS] 1. A band of radio frequencies allocated for a particular purpose; a standard broadcasting channel is 10 kilohertz wide, a television channel 6 megahertz wide. 2. A path through which electrical transmission of information takes place. [COMPUTER SCIENCE] 1. A path along which digital or other information may flow in a computer. 2. The section of a storage medium that is accessible to a given reading station in a computer, such as a path parallel to the edge of a magnetic tape or drum or a path in a delay-line memory. 3. One of the longitudinal rows of intelligence holes punched along the length of paper tape.Also known as level. 4. A device or portion of a computer that controls and stores data and transfers information between the computer and peripheral equipment. [ELECTRONICS] 1. A path for a signal, as an audio amplifier may have several input channels. 2. The main current path between the source and drain electrodes in a field-effect transistor or other semiconductor device. [ENGINEERING] The forming of cavities in a gear lubricant at low temperatures because of congealing. [HYDROLOGY] The deeper portion of a waterway carrying the main current. [NAVIGATION] Navigable portion of a body of water. [NUCLEONICS] A passage for fuel slugs or heat-transfer fluid in a reactor. [PETROLEUM ENGINEERING] In a drilling operation, a cavity appearing behind the casing because of a defect in the cement.
{ 'chan•əl }

  Score: 1.00

- **aa channel** [GEOLOGY] A narrow, sinuous channel in which a lava river moves down and away from a central vent to feed an aa lava flow.
{ ä'ä 'chan•əl }

  Score: 0.10 (possible misspelling in search term)

- **abandoned channel** See oxbow
{ ə'ban•dənd 'chan•əl }

  Score: 0.10 (possible misspelling in search

- **adjacent-channel interference** [COMMUNICATIONS] Interference that is caused by a transmitter operating in an adjacent channel when the side bands of the adjacent-channel transmitter beat with the carrier signal of the desired station.Also known as monkey chatter; side-band interference; side-band splash.
{ ə'jā s•ənt 'chan•əl in•tər'fir•əns }

Score: 0.10 (possible misspelling in search term)

- **adjacent-channel selectivity** [ELECTRONICS] The ability of a radio receiver to respond to the desired signal and to reject signals in adjacent frequency channels.
  { əˈjā s•ənt ˈchan•əl səˌlekˈtiv•əd•ē }

Score: 0.10 (possible misspelling in search term)

- **all-channel tuning** [COMMUNICATIONS] The ability of a television set to receive ultra-high-frequency as well as very-high-frequency channels.
  { ˈȯl ˌchan•əl ˈtün•iŋ }

Score: 0.10 (possible misspelling in search term)

- **alternate-channel interference** [COMMUNICATIONS] Interference that is caused in one communications channel by a transmitter operating in the next channel beyond an adjacent channel.Also known as second-channel interference.
  { ¦ȯl•tər•nət ¦chan•əl in•tərˈfir•əns }

Score: 0.10 (possible misspelling in search term)

- **American standard channel** [CIVIL ENGINEERING] A C-shaped structural member made of hot-rolled structural steel.
  { əˈmer•ə•kən ˈstan•dərd ˈchan•əl }

Score: 0.10 (possible misspelling in search term)

- **analog channel** [ELECTRONICS] A channel on which the information transmitted can have any value between the channel limits, such as a voice channel.
  { ˈan•əlˌäg ˈchan•əl }

Score: 0.10 (possible misspelling in search term)

- **autonomous channel operation** [COMPUTER SCIENCE] The rapid transfer of data between computer peripherals and the main store in which an entire block of data is transferred, word by word; the cycles of storage time for the word transfer are stolen from those available to the central processing unit.
  { ȯˈtän•ə•məs ¦chan•əl ˌäp•əˈrā•shən }

Score: 0.10 (possible misspelling in search term)

- **aux channel** See auxiliary channel

Score: 0.10 (possible misspelling in search

- **auxiliary channel** [COMMUNICATIONS] A secondary path for low-speed communication that uses the same telephone line as a higher-speed stream of data. Abbreviated aux channel.
  { ȯgˈzil•yə•rē ˈchan•əl }

Score: 0.10 (possible misspelling in search term)

- **block multiplexor channel** [COMPUTER SCIENCE] A transmission channel in a computer system that can simultaneously transmit blocks of data from several high-speed input/output devices by interleaving the data.

{ 'bläk ˈməlt•iˌplek•sər ˌchan•əl }

Score: 0.10 (possible misspelling in search term)

- **boghead cannel shale** [GEOLOGY] A coaly shale that contains much waxy or fatty
{ 'bägˌhed ˈkan•əl ˌshāl }

Score: 0.10 (possible misspelling in search term)

- **broad-band channel** [COMMUNICATIONS] A data transmission channel that can handle frequencies higher than the normal voice-grade line limit of 3 to 4 kilohertz; can carry many voice or data channels simultaneously or can be used for high-speed single-channel data transmission.
{ 'brȯd ˌband ˈchan•əl }

Score: 0.10 (possible misspelling in search term)

- **buffered I/O channel** [COMPUTER SCIENCE] A storage device located between input/output (I/O) channels and main storage control to free the channels for use by other operations.
{ 'bəf•ərd ˈīˈō ˌchan•əl }

Score: 0.10 (possible misspelling in search term)

- **bypass channel** [CIVIL ENGINEERING] 1. A channel built to carry excess water from a stream.Also known as flood relief channel; floodway. 2. A channel constructed to divert water from a main channel.
{ 'bīˌpas ˌchan•əl }

Score: 0.10 (possible misspelling in search term)

- **byte multiplexor channel** [COMPUTER SCIENCE] A transmission channel in a computer system that can transmit data simultaneously from several devices and only one byte at a time.
{ 'bīt 'məlt•iˌplek•sər ˌchan•əl }

Score: 0.10 (possible misspelling in search term)

- **cannel coal** [GEOLOGY] A fine-textured, highly volatile bituminous coal distinguished by a greasy luster and blocky, conchoidal fracture; burns with a steady luminous flame.Also known as cannelite.
{ 'kan•əl ˌkōl }

Score: 0.10 (possible misspelling in search term)

- **cannel shale** [GEOLOGY] A black shale formed by the accumulation of an aquatic ooze rich in bituminous organic matter in association with inorganic materials such as silt and clay.
{ 'kan•əl ˌshāl }

Score: 0.10 (possible misspelling in search term)

1 2 3 4 5 6 7 8 NEXT ▶▶I

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EXHIBIT F

Engineering & Materials: Electrical & Electronics
Engineering:Physical electronics

Transistor

A solid state device involved in amplifying small electrical signals and in processing of digital information. Transistors act as the key element in amplification, detection, and switching of electrical voltages and currents. They are the active electronic component in all electronic systems which convert battery power to signal power. Almost every type of transistor is produced in some form of semiconductor, often single-crystal materials, with silicon being the most prevalent. There are several different types of transistors, classified by how the internal mobile charges (electrons and holes) function. The main categories are bipolar junction transistors (BJTs) and field-effect transistors (FETs).

Single-crystal semiconductors, such as silicon from column 14 of the periodic table of chemical elements, can be produced with two different conduction species, majority and minority carriers. When made with, for example, 1 part per million of phosphorus (from column 15), the silicon is called *n*-type because it adds conduction electrons (negative charge) to form the majority carrier. When doped with boron (from column 13), it is called *p*-type because it has added positive mobile carriers called holes. For *n*-type doping, electrons are the majority carrier while holes become the minority carrier. For *p*-type doping holes are in larger numbers, hence are the majority carriers, while electrons are the minority carriers. All transistors are made up of regions of *n*-type and *p*-type semiconducting material. See also: Semiconductor; Single crystal

The bipolar transistor has two conducting species, electrons and holes. Field-effect transistors can be called unipolar because their main conduction is by one carrier type, the majority carrier. Therefore, field-effect transistors are either *n*-channel (majority electrons) or *p*-channel (majority holes). For the bipolar transistor, there are two forms, n^+pn and p^+np, depending on which carrier is majority and which is the minority in a given region. As a result the bipolar transistor conducts by majority as well as by minority carriers. The n^+pn version is by far the most used as it has several distinct performance advantages, as does the *n*-channel for the field-effect transistors. (The n^+ indicates that the region is more heavily doped than the other two regions.)

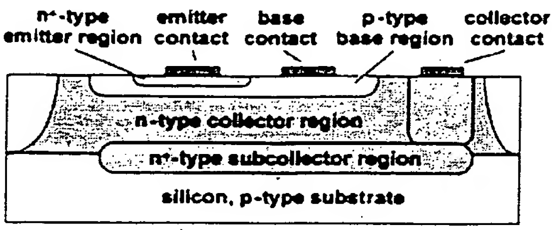
Bipolar transistors

Bipolar transistors have additional categories: the homojunction for one type of semiconductor (all silicon), and heterojunction for more than one (particularly silicon and silicon-germanium, $Si/Si_{1-x}Ge_x/Si$). At present the silicon homojunction, usually called the BJT, is by far the most common. However, the highest performance (frequency and speed) is a result of the heterojunction bipolar transistor (HBT).

Bipolar transistors are manufactured in several different forms, each appropriate for a particular application. They are used at high frequencies, for switching circuits, in high-power applications, and under extreme environmental stress. The bipolar junction transistor may appear in discrete form as an individually encapsulated component, in monolithic form (made in and from a

common material) in integrated circuits, or as a so-called chip in a thick-film or thin-film hybrid integrated circuit. In the *pn*-junction isolated integrated-circuit n^+pn bipolar transistor, an n^+ subcollector, or buried layer, serves as a low-resistance contact which is made on the top surface (Fig. 1). See also: Integrated circuits; Junction transistor

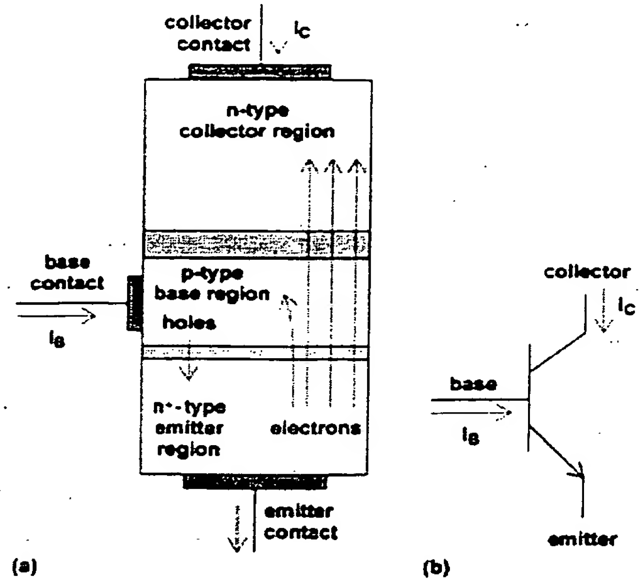
Fig. 1 Isolated n^+pn bipolar junction transistor for integrated-circuit operation.



Basic operation

The n^+pn bipolar transistor (Fig. 2 *a*) has three differently doped regions and two junctions, the emitter-base junction and the collector-base junction, in a single crystal of silicon. It is possible to describe a large part of bipolar tansistor operation by interpreting the device somewhat like a pair of back-to-back diodes. The emitter-base junction is usually forward-biased; that is, the voltage of the base with respect to the emitter, V_{BE}, is greater than 0. This voltage is small (less than 1 V), but the forward current across the junction is relatively large, just as in the forward-biased diode. The majority carriers in the emitter region (n^+-type) are electrons. These are injected across the emitter-base junction into the base region (*p*-type), which is quite thin, being on the order of 0.1-0.5 micrometer. With the base-collector junction reversed-biased (that is, the voltage of the collector with respect to the base, V_{CB}, is greater than 0), the holes that are present in the *p*-type base material do not cross it, as they are repelled by the electric field from the collector. However, the electrons that have been injected from the emitter into the very thin base region (where they become minority carriers) diffuse across the base-collector junction and are then collected under the influence of the positive collector potential (Fig. 2 *a*). This electron current across the base-collector junction is almost as large as the electron current crossing from the emitter into the base region. In general, it runs from 99.5 to 99.99% of the emitter current, the small decrease being accounted for by electrons that are lost in the narrow base region. In terms of electron currents, for every 200 electrons flowing into the emitter from the external contact and crossing into the base region, perhaps one causes a current in the base lead, whereas 199 cross over into the collector and flow out into the external collector circuit. See also: Diffusion; Junction diode; Semiconductor diode

Fig. 2 Operation of an n^+pn bipolar junction transistor. (*a*) Conceptual cross section with carrier flows. (*b*) Circuit symbol.



The total current across any junction results from both hole and electron motion. In the emitter, electrons are injected from the n^+ region into the p region of the base, while holes are injected from the p-type base back into the emitter. These holes also cause current to flow into the base lead. The sum of these two currents crossing the junction determines the total emitter current. Even though holes and electrons flow in opposite directions, they add together as total current. However, in the emitter-base junction this hole current is usually several orders of magnitude less than the electron current, a consequence of much heavier doping in the emitter region compared to the base. The total base current is made up of two small components: the holes injected from the base to the emitter, and the electrons lost from the emitter due to recombination in the base. It is desirable for the base current to be as close to zero as possible, in order to obtain large current gains from base to collector.

Circuit symbol

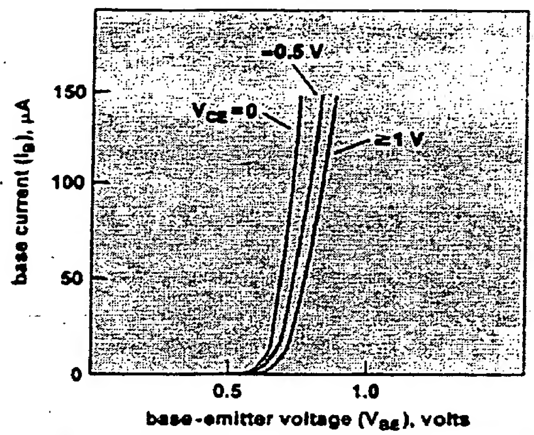
The circuit symbol for an n^+pn bipolar transistor (Fig. 2*b*) has an arrowhead on the emitter lead whose direction indicates that electrons flowing in from the emitter to the base are the same as if positive charges were leaving that terminal. Hence, the arrowhead points out of the emitter.

Voltage-current characteristics

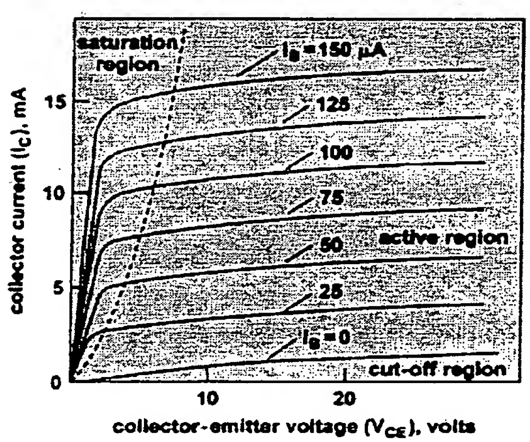
The input voltage-current characteristics of an n^+pn transistor (Fig. 3 *a*) are a family of curves of base current, I_B, versus base-emitter voltage, V_{BE}, for various values of collector-emitter voltage, V_{CE}. The output characteristics (Fig. 3 *b*) are curves of collector current, I_C, versus collector-emitter voltage, V_{CE}, with the base current, I_B, as an independent parameter. These curves display two general characteristics. First, once the collector-emitter voltage is greater than 1 or 2 V, the collector current is relatively independent of this voltage; that is, each curve flattens out. Second, in this region the collector current is about 100 times the base current. The ratio of collector current to base current with the collector base voltage, V_{BE}, equal to zero is defined as the dc beta (β_{dc}) for the bipolar transistor.

Fig. 3 Voltage-current characteristics of a typical low-power n^+pn bipolar transistor. (*a*) Input

characteristics: base current (I_B) versus base-emitte voltage (V_{BE}) for various values of collector-emitter voltage (V_{CE}). When $V_{CE} > 1$ V, the curves coincide. (*b*) Output characteristics: collector current (I_C) versus collector-emitter voltage (V_{CE}) for various values of base current (I_B). (*After W. H. Hayt, Jr., and G. W. Neudeck, Elecronic Circuit Analysis and Design, 2d ed., reprint, Wiley, 1995*)



(a)



(b)

The voltage-current characteristics emphasize the regions where the emitter-base junction is forward-biased (the base-emitter voltage, V_{BE}, is greater than 0) and the collector-base junction is reverse-biased (the collector-base voltage, , is greater than 0). These bias conditions define the active region for a bipolar transistor, which is mainly used for analog circuits. A quick glance at the input characteristics shows that the base current is greater than 0 under these conditions. When both junctions are reverse-biased, any currents that flow are several orders of magnitude smaller, and this is termed the cutoff region ("off" for digital circuits). The condition that both junctions are forward-biased defines the saturation region or the "on" region for digital circuits. Both the base-emitter voltage, V_{BE}, and the base-collector voltage, V_{BC}, are small positive values; and the collector-emitter voltage, V_{CE}, their difference, is also small and positive. The boundary between the active and saturation regions occurs where the collector-base voltage, V_{CB}, equals 0.

+*np*transist r">*p*$^+$*np* transistor

The p^+np transistor contains a narrow n-type base layer sandwiched between p-type emitter and collector regions. Forward bias on the emitter-base junction causes holes to be injected into the base region, most of which diffuse across the thin base and are collected by the reverse-biased base-collector junction. The total emitter current, I_E, is thus composed of the sum of this large hole current plus a much smaller electron current directed from the base toward the emitter.

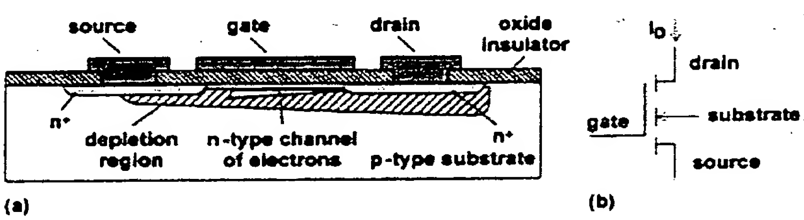
Field-effect transistors

Majority-carrier field-effect transistors are classified as metal-oxide-semiconduc- tor field-effect transistor (MOSFET), junction "gate" field-effect transistor (JFET), and metal "gate" on semiconductor field-effect transistor (MESFET) devices. MOSFETs are the most used in almost all computers and system applications. However, the MESFET has high-frequency applications in gallium arsenide (GaAs), and the silicon JFET has low-electrical noise performance for audio components and instruments. In general, the n-channel field-effect transistors are preferred because of larger electron mobilities, which translate into higher speed and frequency of operation.

MOSFETs

An n-channel MOSFET (Fig. 4) has a so-called source, which supplies electrons to the channel. These electrons travel through the channel and are removed by a drain electrode into the external circuit. A gate electrode is used to produce the channel or to remove the channel; hence it acts like a gate for the electrons, either providing a channel for them to flow from the source to the drain or blocking their flow (no channel). With a large enough voltage on the gate, the channel is formed, while at a low gate voltage it is not formed and blocks the electron flow to the drain. This type of MOSFET is called enhancement mode because the gate must have sufficiently large voltages to create a channel through which the electrons can flow. Another way of saying the same idea is that the device is normally "off" in an nonconducting state until the gate enhances the channel.

Fig. 4 An n-channel enhancement-mode metal-oxide-semiconductor field-effect transistor (MOSFET). (*a*) Cross section. (*b*) Standard circuit symbol.



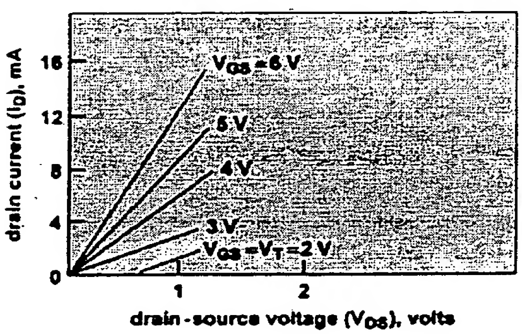
An n-channel MOSFET with a positive gate-source voltage, V_{GS}, and a small drain-source voltage, V_{DS}, has an electric field established across an insulating layer (Fig. 4). This field acts to repel positive carriers (holes) in the substrate and to attract negative carriers (electrons). As a result, a layer of substrate near the insulator becomes less p-type and its conductivity is reduced. As the gate-source voltage increases further, this surface region of the substrate eventually has more electrons than holes, and it inverts to n-type. Additional increases in gate voltage add more electrons to the channel and make it even more conductive. This n-channel (Fig. 4*a*) now conducts electrons from the n^+ source to the n^+ drain which has a positive voltage and attracts electrons. Between the p-type substrate and the n-type channel is a depletion (transition) region that serves to isolate the substrate from the channel, a process referred to as self-isolation. Since conduction is by electrons, the majority carrier, the MOSFET is a majority-carrier device.

The smallest value of the gate-source voltage, V_{GS}, that will produce a channel and a resultant value of drain current, I_D, greater than the few nanoamperes is called the threshold voltage, V_T, typically 0.2-2 V. V_T output voltage-current characteristics of the device are a family of curves of drain-current, I_D, versus drain-source voltage, V_{DS}, for several values of gate-source voltage, V_{GS} (Fig. 5). When the drain-source voltage is small (Fig. 5 *a*), the device behaves as a voltage-controlled linear resistance. When the drain-source voltage becomes sufficiently large (Fig. 5*b*), the gate-to-drain voltage is less than the threshold voltage, that is, Eq. (1)

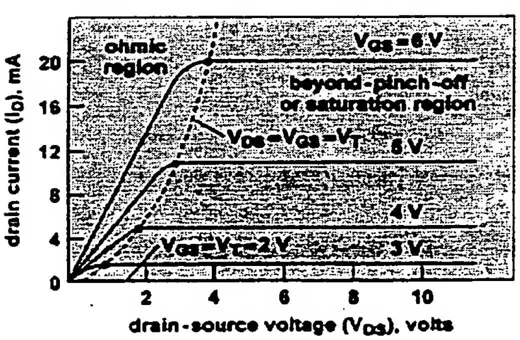
$$V_{GD} = V_{GS} - V_{DS} \leq V_T \tag{1}$$

holds, and pinch-off occurs at the drain end of the channel. Further increases in drain-source voltage do not lead to larger values of drain current, (that is, the current saturates), since the transistor is operating in the region beyond pinch-off. In this region of operation the MOSFET device behaves as a voltage-controlled current source.

Fig. 5 Output characteristics of *n*-channel enhancement-mode MOSFET: drain current (I_D) versus drain-source voltage (V_{DS}) for various values of gate-source voltage (V_{GS}). (*a*) Small values of V_{DS}, where the device behaves as a voltage-controlled linear resistance. (*b*) Complete output characteristics. (*After W. H. Hayt, Jr., and G. W. Neudeck, Electronic Circuit Analysis and Design, 2d ed., reprint, Wiley, 1995*)



(a)



(b)

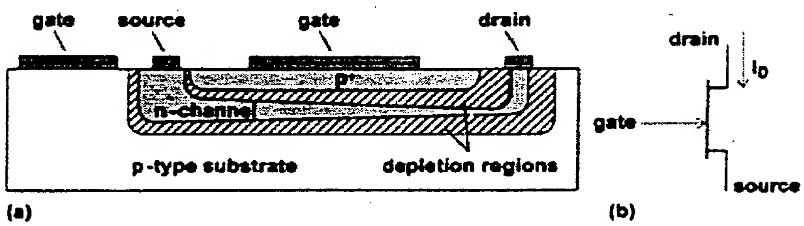
The standard circuit symbol for the *n*-channel enhancement-mode MOSFET (Fig. 4*b*) shows the substrate as a separate connector. An arrow shows the direction from the *p* side (substrate) to the *n* side (channel) of the junction, while a segmented line indicates the enhancement mode; no channel is present until channel enhancement occurs at which point the gate-source voltage exceeds the threshold voltage.

The p-channel enhancement-mode MOSFET is the complement of the n-channel device. It has an n-type silicon substrate in which a p-type channel is induced (enhanced) by making the gate sufficiently negative that the gate-source voltage is less than the threshold voltage. The gate of a p-channel enhancement-mode MOSFET has an electric field between the gate and substrate which pushes out electrons, attracts holes, and eventually inverts the channel to p type. Now holes conduct between the p^+ source and drain electrodes.

JFETs

In the JFET (Fig. 6 *a*), a conducting majority-carrier n channel exists between the source and drain. When a negative voltage is applied to the p^+ gate, the depletion regions widen with reverse bias and begin to restrict the flow of electrons between the source and drain. At a large enough negative gate voltage (symbolized V_P), the channel pinches off. The standard circuit symbol (Fig. 6*b*) has a continuous bar since current flows with zero gate-source voltage, V_{GS}, at larger values of the drain source voltage, V_{DS}.

Fig. 6 An n-channel junction field-effect transistor (JFET). (*a*) Cross section. (*b*) Circuit symbol.



MESFETs

The MESFET is quite similar to the JFET in its mode of operation. A conduction channel is reduced and finally pinched off by a metal Schottky barrier placed directly on the semiconductor. Metal on gallium arsenide is extensively used for high-frequency communications because of the large mobility of electrons, good gain, and low noise characteristics. Its cross section is similar that of the JFET (Fig. 6*a*), with a metal used as the gate. See also: Schottky barrier diode

High-frequency transistors

High-frequency effects for the bipolar transistor are characterized by the emitter charging time (τ_e), the collector charging time (τ'_c), the minority-carrier transit time through the active base region (τ_b), and the base-collector depletion region transit time (τ_c). The emitter charging time equals the product of the emitter-base capacitance (proportional to the area of the emitter) and the thermal voltage divided by the dc current. The minority-carrier transit time through the active base region is approximately the square of the active width of the base region divided by twice the diffusion constant for the minority carriers that diffuse through the base. (The dependence on the active width indicates the need for a very thin base region.) The transit time through the collector-to-base depletion region equals the width or this region divided by twice a saturated velocity to which the carriers can accelerate. Thus, a short transit time requires a large saturated velocity or a small width, which means a small value of the collector-to-base voltage. The final term for the collector is its charging time, approximately the product of the collector contact resistance and the collector-base capacitance. A short charging time thus requires a small value of the former and a small collector area to reduce the latter.

Figures f merit

A figure of merit for the advanced bipolar transistor is the frequency, f_T, at which the short-circuit, current-signal gain is unity. This frequency equals the inverse of the sum of the four times discussed above, τ_e, τ_b, τ_c, and τ'_c. A large value of f_T indicates that the intrinsic device is fast.

A more circuit-oriented figure of merit is f_{max}, the maximum frequency that gain can still be achieved in a circuit, given by Eq. (2) .

$$f_{\max} \cong \sqrt{\frac{f_T}{8\pi R_b C_{cb}}} \tag{2}$$

Here the external base resistance, R_b, is important, as well as the base-collector area needed to reduce the collector base capacitance, C_{cb}.

Most very high speed logic circuits belong to the emitter-coupled logic (ECL) family of circuits or the current-mode logic (CML) family. The figure of merit for this type of circuit is given by Eq. (3) , where R_c is the collector resistance,

$$\tau_{cs} = 1.7\sqrt{\frac{(R_c + 2R_b)(3C_{cb} + C_{cs})}{2\pi f_{T\,\max}}} \tag{3}$$

C_{cs} is the collector-substrate capacitance of the integrated bipolar transistor, and $f_{T\,max}$ is the peak value of f_T when the collector current is varied. Again, this expression indicates the need for thin base regions, small emiter and collector areas, and low values of resistances contacting the device. See also: Logic circuits

Structural improvements

The function of the sub-collector in the integrated-circuit bipolar transistor (Fig. 1) is to reduce the collector resistance. Typical values of the current gain, that is, the dc beta, range from 80 to 300, and f_T ranges from 5 to 45 GHz with values of f_{max} up to 450 GHz. In an emitter-coupled logic circuit the transistor has a gate delay of as low as 15 picoseconds. An improvement to this structure is to reduce the sidewall components of capacitance with the local-oxidation-of-silicon (LOCOS) structure. In addition, a polysilicon-contacted emitter can be added to improve the dc beta, and the external base resistance can be reduced by increased base doping, somewhat similar to what is done in heterojunction bipolar transistors.

Single, self-aligned transistor

The single self-aligned bipolar transistor (SST) reduces the emitter area to 0.35 × 5 μm and has f_T values up to 20 GHz and a dc beta of 180. The use of a pedestal collector and double self-alignment improves the value of f_{max} and the emitter charging time by reducing the area and the external parasitic resistances. In all these cases the fabrication methods strive to reduce the area, hence the capacitances.

Heterojunction bipolar transist r

The heterojunction bipolar transitor is made from two different types of semiconductor material. The most promising is the silicon-germanium type. It is produced by epitaxially growing a

narrow band-gap base region of heavily doped p-type $Si_{1-x}Ge_x$ on an n-type silicon collector and then capping it with an n^+ type silicon emitter. The silicon-germanium compound suppresses the base-injected holes (Fig. 2), and at the same time this allows the base to be doped very heavily to reduce the external base resistance. By grading the germanium content and the doping, f_T, values up to 32 GHz and f_{max} of 120 GHz have been achieved, with good values of beta. The circuit delay is about 20 ps. Other heterojunction bipolar transistors of interest include those using the compound semiconductors GaAlAs/GaAs, InGaP/GaAs, and InGaAs/InP. These devices have achieved f_T values of 37 GHz and f_{max} of 90 GHz with powers of 1-5 W. See also: Semiconductor

High-frequency field-effect transistors

The inability of the MOSFET to conduct large currents into capacitive loads has limited its use in extremely high-frequency circuits. However, because of its low power consumption it can be integrated into very dense circuits. The first requirement is that the channel length be small (approximately 1 μm), as it controls how fast the majority carrier can traverse between the source and drain. The carrier mobility must also be large; hence, electrons are preferred, as their mobility is typically two to three times larger than holes. A second requirement is for low values of source and drain resistance. In circuit applications a small value of capacitance between the gate and drain is necessary to reduce the total effective capacitance that is multiplied by the circuit voltage gain. Self-aligned gates, polysilicon, and channel lengths of less than 0.15 μm are used. Typical performance characteristics for a 0.5-μm gate length are an f_T of 10 GHz and an f_{max} of 15 GHz. In complementary metal-oxide-semiconductor (CMOS) circuits with gate lengths of 0.15 μm, gate delays as low as 21 ps per stage are possible.

The more advanced techniques use silicon-on-insulator (SOI) technology to further reduce the external parasitic capacitances around the source and drain. Other device structures include the high electron mobility transistor (HEMT), silicon-germanium MOSFETs, and combinations of bipolar transistors and MOSFETs (BiCMOS). Each technology has its particular advantages. The HEMT is produced from compound semiconductors and can yield an f_T of 300 GHz with gate delays of 25 ps. See also: Microwave solid-state devices

Gerold W. Neudeck

Models

Whether the transistor is used in the design of small analog circuits or very large scale integrated circuits, its behavior has to be adequately understood by the designer. Analysis of the circuit is a prerequisite to its fabrication, thus pointing to the need for models. The higher levels of integration as well as of the cost of fabrication have increased the need for more accurate models and also their complexity. Circuit simulation programs have become rather commonplace and generally available for use on personal computers. The usefulness of such computer-aided design programs is directly influenced by the accuracy of the transistor models and their adequacy for the design application. In general the models can be categorized as large-signal (nonlinear) models used for dc or transient analysis, and small-signal (linear) models used for ac or frequency-domain analysis.

Most large-signal models are represented by systems of equations relating currents and charges to terminal voltages. Different equations are typically used for different combinations of terminal voltages or regions of operation.

In many analog circuits, the signals are small enough that the nonlinear models can be replaced

by linearized equivalent circuit models. Linear circuits are much less complicated to analyze than nonlinear ones. The hybrid-π configuration can be used for linear modeling of field-effect transistors of bipolar junction transistors. See also: Amplifier; Circuit (electronics); Electrical model

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Robert M. Fox

BIBLIOGRAPHY

- W. H. Hayt, Jr., and G. W. Neudeck, *Electronic Circuit Analysis and Design*, 2d ed., 1984, reprint 1995
- Institute of Electrical and Electronics Engineers, *1994 International Electron Devices Meeting Technical Digest*, San Francisco, California, December 11-14 1994
- G. Massobrio and P. Antognetti, *Semiconductor Device Modeling with SPICE*, 2d ed., 1998
- G. W Neudeck, *The Bipolar Transistor*, 2d ed., 1989
- G. W. Neudeck, *The P-N Junction Diode*, 2d ed., 1989

DOI 10.1036/1097-8542.705300

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I, Athena P. Stavrakaras, declare under penalty of perjury under the laws of The United States of America that the following is true and correct:

I am employed in the City of Redwood City, in the County of San Mateo, State of California, and an employee of Quinn Emanuel Urquhart Oliver & Hedges, LLP. I am a citizen of the United States, over the age of eighteen (18) years, and not a party to or interested in the within-entitled action. My business address is 555 Twin Dolphin Drive, Suite 560, Redwood City, California 94065.

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I caused the above documents to be served on each person listed below by the following means:

[FD] Jai H. Rho, Esq. Hogan & Hartson L. Biltmore Tower 500 South Grand Avenue, Suite 1900 Los Angeles, California 90071	**[FD] Sang N. Dang, Esq. Vincent K. Yip, Esq. Alschuler Grossman Stein & Kahan LLP 1620 26th Street, Fourth Floor North Tower Santa Monica, California 90404-4060**

[] I enclosed true and correct copies of said document(s) in an envelope and placed it for collection and mailing with the United States Post Office on February 3, 2003, following the ordinary business practice.
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[X] I enclosed true and correct copies of said documents in an envelope, and placed it for collection and mailing via Federal Express on February 3, 2003, for guaranteed delivery on February 4, 2003, following the ordinary business practice.
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I am readily familiar with my firm's practice for collection and processing of correspondence for delivery in the manner indicated above, to wit, that correspondence will be deposited for collection in the above-described manner this same day in the ordinary course of business.

Executed on February 3, 2003, at Redwood Shores, California

Athena P. Stavrakaras

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